Experimental Program for the Princeton Ion Source Test Facility

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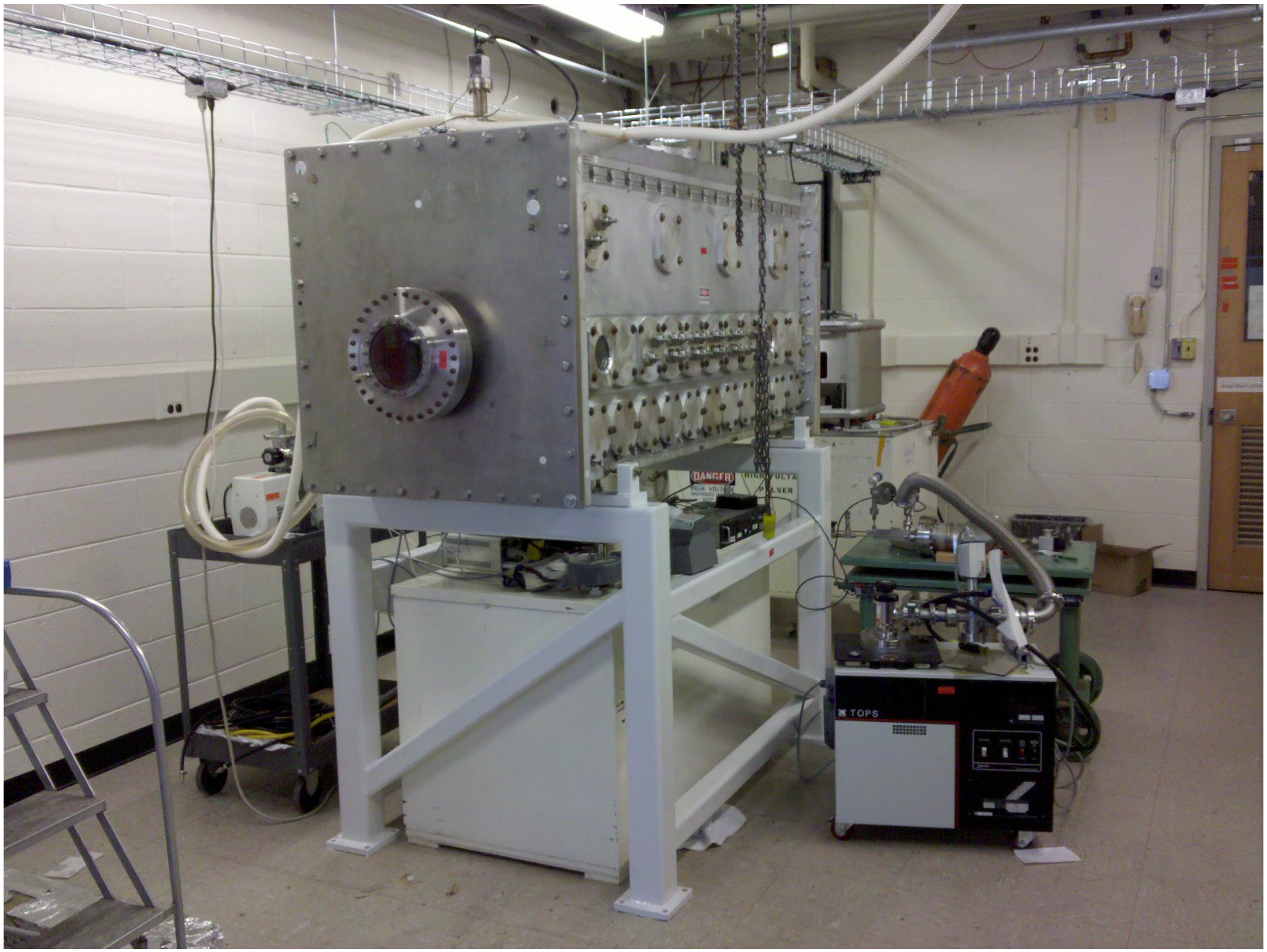
Heavy Ion Fusion Conference 2010
Darmstadt, Germany
August 30 – September 3, 2008

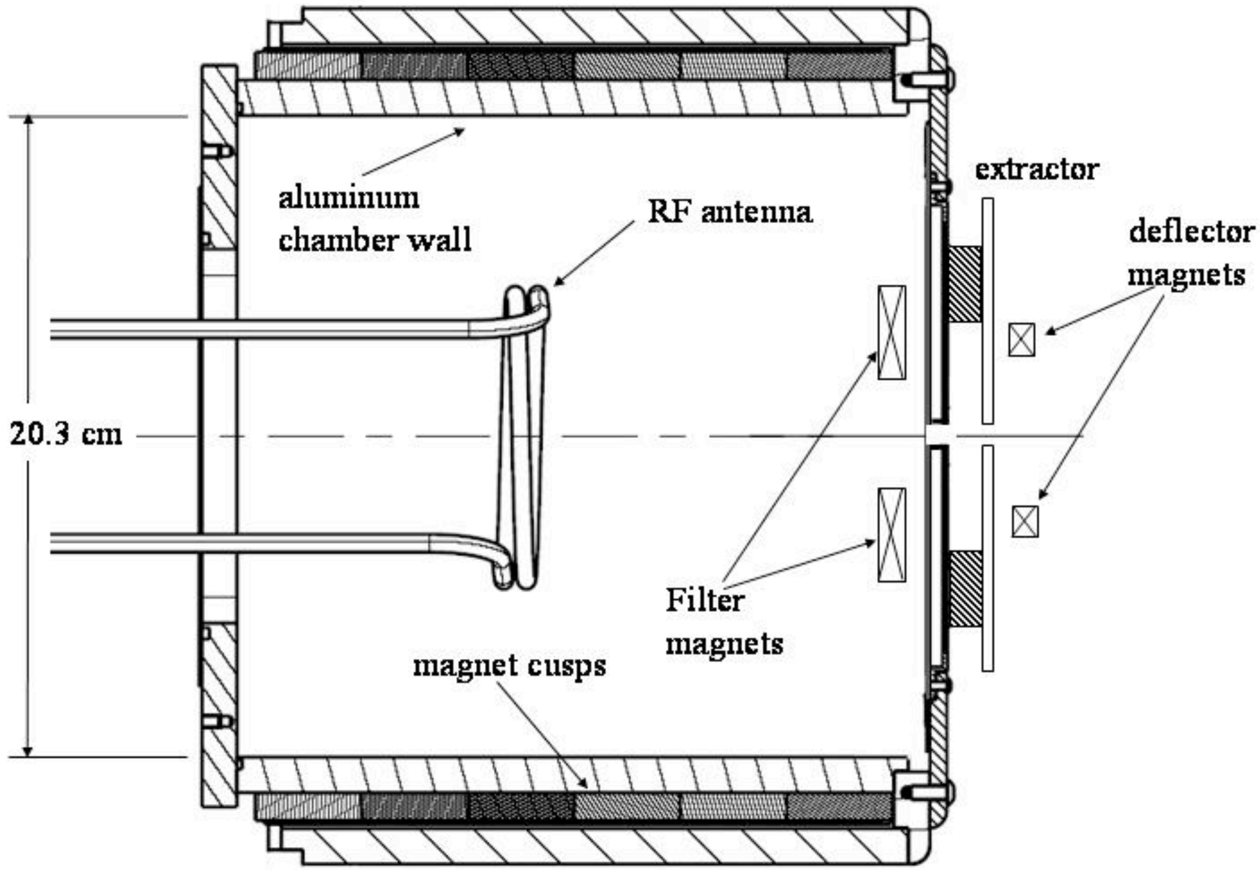
Former STS-100 Test Stand Moved to Princeton, Being Recommissioned as Princeton Ion Source Test Facility

- 100 kV power supply for beam extraction
- 18 kW 13.56 MHz RF supply for ion source
- RF ion source
- Some diagnostics: emittance scanner and Faraday cup
- Excellent diagnostic access through many ports

Test Facility Being Installed at Princeton



Ion Source Used for Chlorine, Argon Comparison Experiment



Tandem volume source with hot electron driver plasma separated by magnetic filter (320 gauss-cm; 68 gauss at extractor) from extractor plasma with cooler electrons

Some of the Topics which May Be Studied on the Princeton Ion Source Test Facility

- **Magnetic insulation for electrostatic accelerators (ref. below)**
- **Plasma sources for beam space charge neutralization**
- **Flash heating of aluminosilicate ion sources [Joe Kwan]**
- **Negative and positive halogen ion beams**
- **Ion – Ion plasmas comprised of positive and negative ions**

GRISHAM, L. R. , Magnetic insulation to improve voltage holding in electrostatic accelerators., *Plasma Physics* 16, 043111 -1 – 043111-5 (2009).

The Electric Field Gradient which can be Sustained Is a Basic Design Constraint of All Electrostatic Accelerators

- Several initiating sources of arcs in electrostatic accelerators:

1. Electron field emission from microprojections (spontaneous emission)

   most ubiquitous source of arcs

   birth energy of electrons is about temperature of electrode

2. Photoemission due to ultraviolet light, X-rays, or gammas

   electron birth energy can be higher than thermal

3. Secondary emission due to impact of ions, electrons, or energetic neutrals

   electron birth energy higher than thermal

Magnetic Insulation Might Improve Voltage Holding in Electrostatic Accelerators

- Attempt to mitigate breakdowns by passing current along each acceleration stage to produce enveloping magnetic field which is everywhere parallel to surface of accelerator grid and support structure

- Magnetic field needs to be sufficiently strong to prevent electrons from leaving surface and picking up energy from electric field.

Produce Magnetic Field with No Components Normal to Conductors

Thus, spontaneous field emission should be most responsive to magnetic insulation

With room temp of 1/40 eV; 100 G would give gyroradius of 3.8 x 10^{-3} cm; reduce mobility of electrons within electrode and at surface

Photoemission require higher magnetic field, and secondary emission perhaps more

Multistage Electrostatic Accelerators

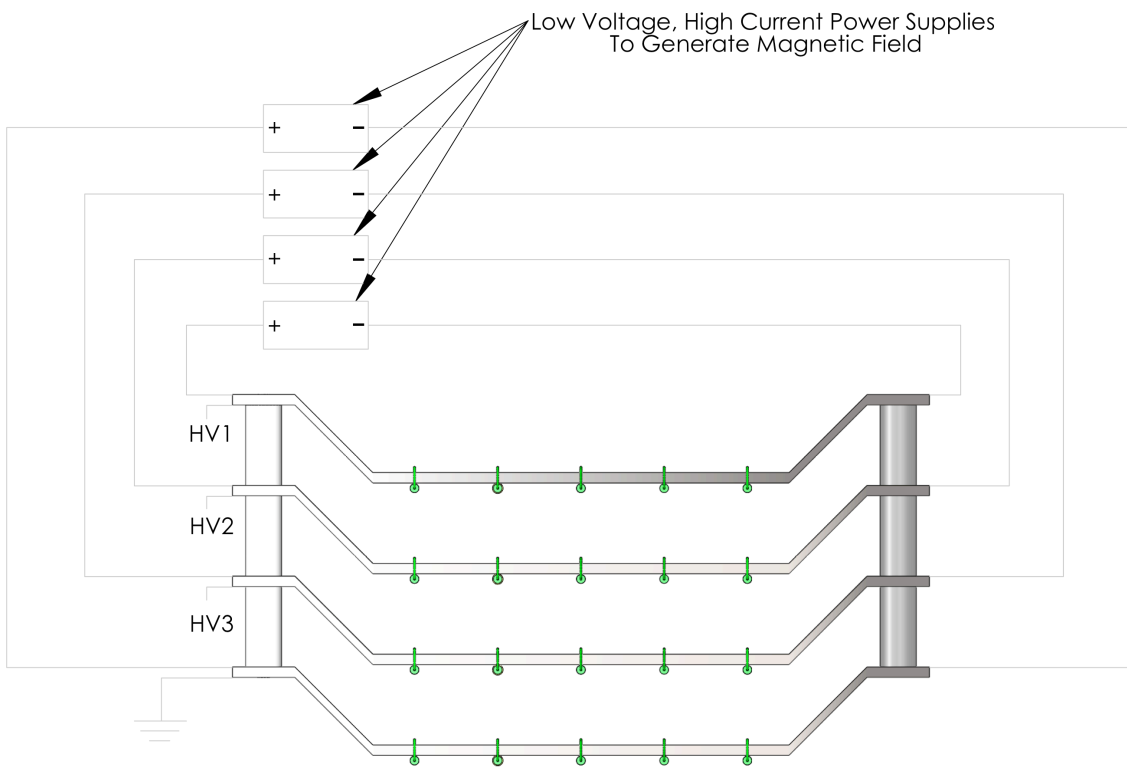
- Can either pass current producing magnetic field in same direction or in alternating directions in successive electrodes

- Same-direction currents will result in small net deflection of ion beam, because field direction switches from one side of electrode to other

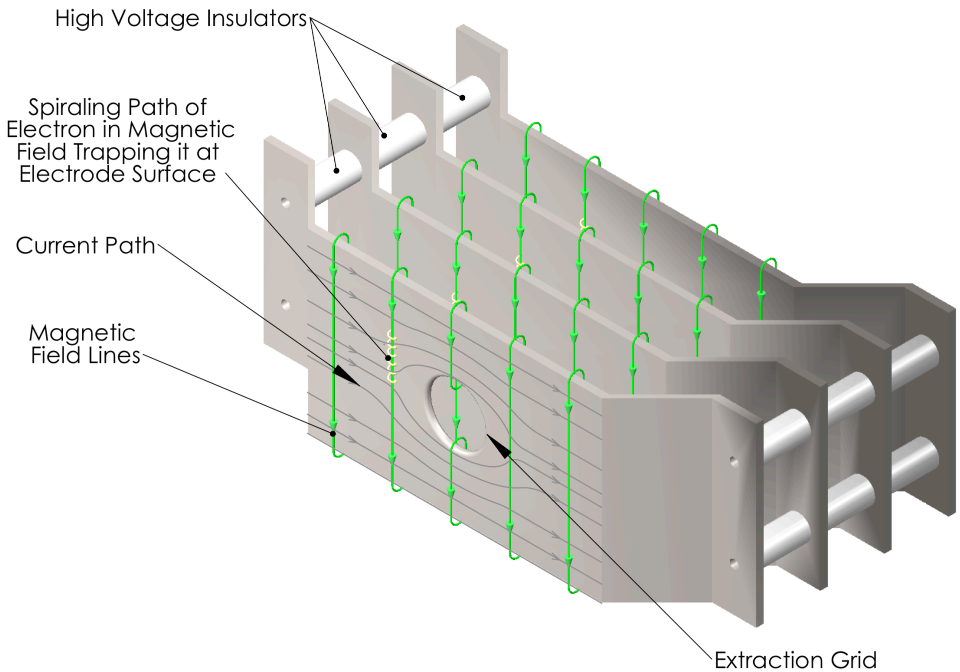
- Alternating-direction currents can produce negligible net ion deflection

- Choice may depend upon tolerable mechanical forces due to fields

Magnetic Insulation Can Either Be Same or Alternate from Stage to Stage with Little Net Ion Deflection



Magnetic Field Is Everywhere Parallel to Surfaces of Electrodes and Their Conducting Support Structures



Simple Experiment Planned to Test Effectiveness of Magnetic Insulation against Spontaneous Field Emission

- Use two polished rectangular copper electrodes with high voltage applied across the vacuum gap between them
- Pass current to form magnetic field through cathode electrode (ground electrode)
- Measure sustainable voltage without magnetic field
- Gradually raise magnetic insulation current, see if sustainable voltage rises
- Not sure how much current density will need, but can adjust gap to try to find one which suits the available high voltage and the available magnetic insulation current supply

If Magnetic Insulation Appears Effective against Spontaneous Field Emission, then Test against other Breakdown Pathways

- Add ultraviolet light source to test whether suppresses photoemission

- Strike cathode with electron beam and ion beam to test suppression of secondary emission

- Try magnetic insulation in accelerator of the test stand ion source

Several Types of Ion Sources Might Be Suitable for Beam Space-Charge Neutralization

- Ferroelectric plasma sources: test geometries and component materials that are different from or variants on the present source in use at NDCX-1

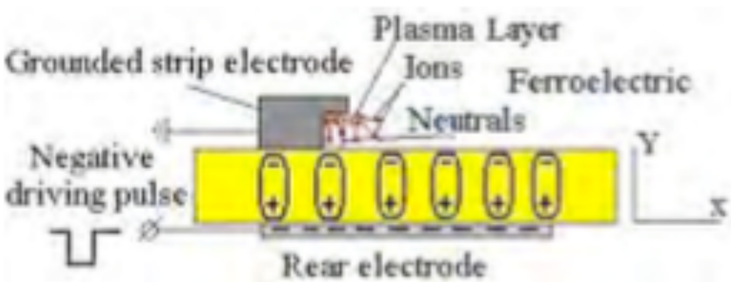
  Try commercial circuit board as the dielectric with surface pads or copper coatings as the electrodes

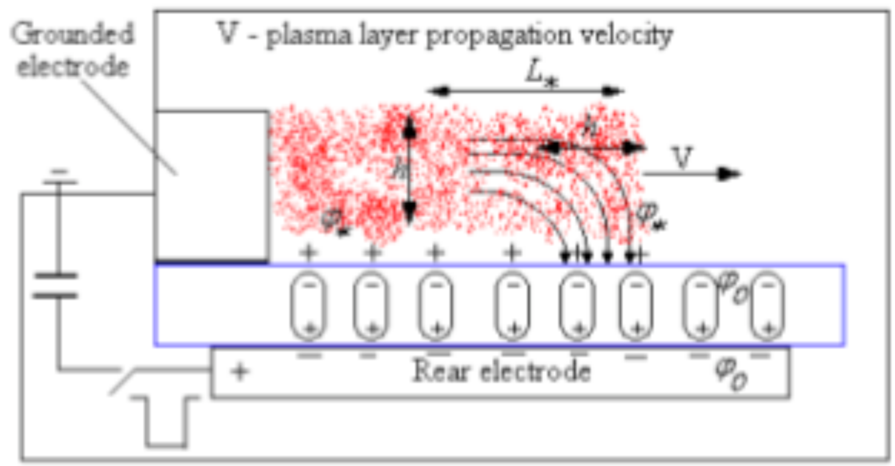
  Try sharper rise and fall times for the voltage pulses

- Laser-ionized plasmas might be attractive alternative; try using excimer laser to ionize jet of gas or vapor

- Laser-ablation of a solid can produce localized high-density plasma

Ferroelectric Sources Are Intrinsically Simple Method for Producing Large Volume Plasmas Rapidly





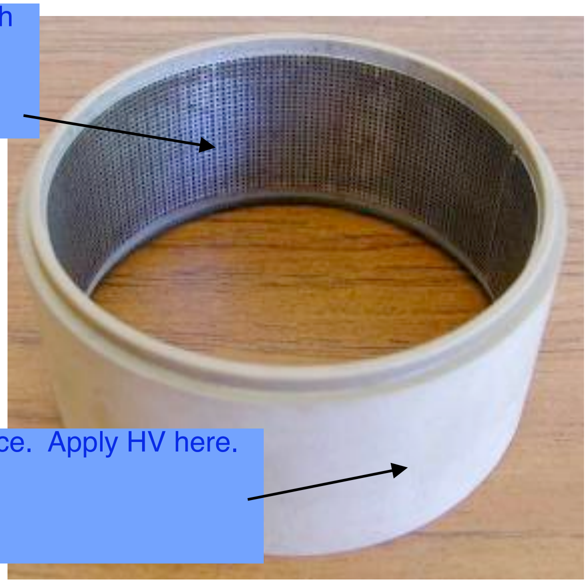
Ferroelectrics Are Materials with Permanent Dipoles (Piezoelectrics)

Ceramics such as Lead Zirconium Titanate and Barium Titanate with relative dielectric coefficients of several thousand. Commonly used in high-power capacitors and transducers.

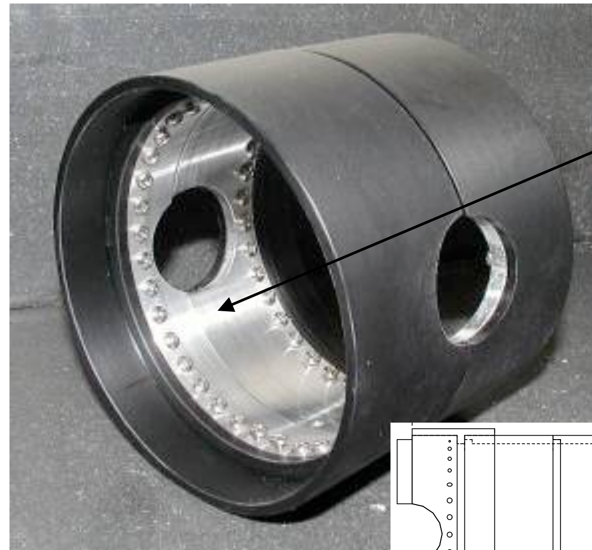
Piezoelectric polymers have many applications, and might also be suitable candidates for experiments, although they might be more susceptible to neutron damage in fusion reactor environments

Barium Titanate ($BaTiO_3$) Ferroelectric Plasma Source (FEPS)

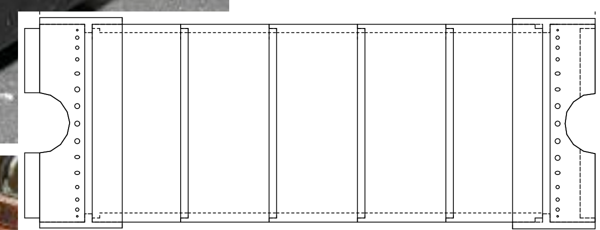
Grounded interior mesh

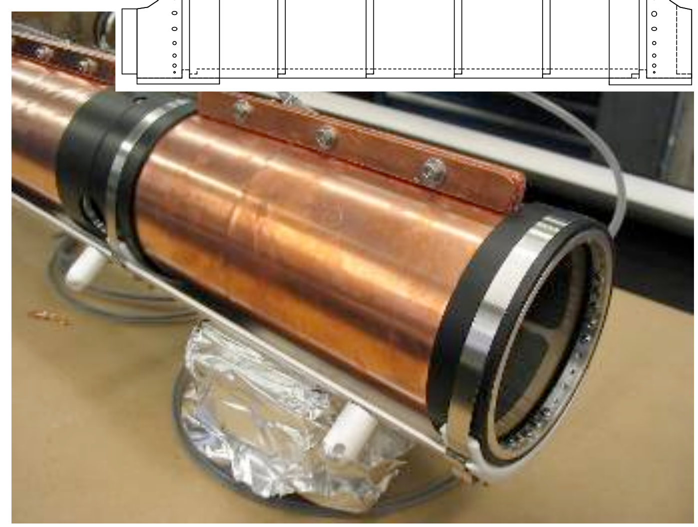


Metalized outer surface. Apply HV here.



Coupling provides grounding and transverse access.





A high-dielectric ($\varepsilon/\varepsilon_0 \sim 1000$) ceramic produces a large polarization surface charge density when a high voltage is applied. The resulting large electric field creates a plasma on the mesh-lined surface.

Short Pulse Beam Control of Aluminosilicate Source

- Conventionally heated by electric resistance heaters
- For HIF, would like shorter, more intense, pulses with higher intensity
- Try flash-heating surface of resistively heated aluminosilicate with xenon flash lamp or excimer laser, extract beam and measure with Faraday cup
- If successful, might not only increase intensity, but increase source lifetime if could pick temperature range such that emission dropped greatly between light pulses.

Excimer Pumped Dye Laser System – Similar to LBNL Laser

XeCl

λ = 308 nm

E_γ = 4.03 eV

Rep. rate = 10 Hz

Energy per pulse = 300 mJ

Pulse duration = 25 ns

Dye laser

Excimer laser

Possible Roles for Halogen Ions in Fusion and Other Fields

- Negative ion beams as drivers for inertial confinement fusion
- Positive ion beams as drivers for inertial confinement fusion
- Ion - Ion plasmas in ion sources for physics studies of effective temperature and sheath properties
- Ion - Ion plasmas in warm dense matter regime (harder to measure properties than in ion source)
- Cold finely focused beams for ion lithography
- Halogen-assisted extraction of D^- and H^- from sources for heating and current drive in ITER and other magnetic fusion energy devices

•Halogens Have Demonstrated Interesting Characteristics that might Help Several Fields

- Cl^- beams have demonstrated current density, emittance,and survivability similar to positive ions, and with manageable co-extracted electrons; should be attractive for heavy ion fusion or other applications.

- Many lines of evidence support existence of ion-ion electron-depleted plasma in extractor region plasma.

- If ion - ion plasmas are really colder than electron - ion plasmas, then halogens might yield finest focused spots of either positive or negative beams for heavy ion fusion or ion lithography in the semiconductor industry

- The sources we used for Cl^- were similar to D^- sources used for magnetic fusion energy; might be able to improve D^- extraction by adding halogens to reduce ambipolar diffusion potential well

- Can perhaps extend study of ion-ion plasmas to warm dense matter regime by heating bromine or iodine foils with ion beams across dE/dX peak, but will be difficult to measure.

Halogen Experimental Program of HIFVNL Did Not Have Time to Do Some Vital Measurements
Plan to Measure on Test Facility at Princeton

- At similar discharge parameters, compare electron current extracted from chlorine discharge with the magnetic filter in place to the electron current extracted from an argon plasma with the same filter.

- Install slot extractor over uniform region, compare emittance of Ar^+, $Cl^+ + Cl_2^+$, Cl^- along slot, where beam optics contribution minimized. Answer question of whether beams from ion – ion plasmas colder than beams from electron – ion plasmas

- Remove magnetic filter; essential for H^-, but may be unnecessary for halogens.

- Measure ion current density from several different radial positions to determine uniformity.

- Increase cusp field strength to improve confinement, increase RF power density, vary filter position.

•Reanimated Test Facility Provides Venue For Exploration of Topics at Tractable Scale

- Hope to produce improvements in:
  - Ion sources
  - Accelerators
  - Space charge neutralizers
  - Understanding of emittance growth with different degrees of space charge neutralization
  - Understanding of ion – ion plasmas, and perhaps of sheaths

End of HIF2010 Presentation
Backup slides follow

•Features of Negative Ion Drivers

- Negative ion beams will not draw electrons from surfaces, so focusing properties will not be contaminated (no electron clouds).

- Negative halogen beams extracted from ion source should not have the low energy charge exchange tails of positive ions.

- If eventually want atomic beams, negative ions can be efficiently converted to atomic beams with photodetachment neutralizers.

- For sufficiently low target chamber pressures, atomic driver beams would reduce average beam self perveance and spot size.

Choice of Beam Element

- Electron affinity determines ease of producing negative ions.

- The halogens F, Cl, I, and Br all have high electron affinities over 3 eV.

- Bromine (mass 81, affinity 3.63 eV) and iodine (mass 127, affinity 3.06 eV) are probably the best mass choices for a heavy ion driver, but require heated sources to produce vapor.

- Fluorine (mass 19, affinity 3.45 eV) and chlorine (mass 37, affinity 3.61 eV) are the easiest choices for a proof-of-principle source because they are diatomic gases at room temperature.

- Chose chlorine because it is easier to handle.

Halogen Ion Sources

- Halogens form negative ions by dissociative attachment of low energy electrons to vibrationally excited diatomic molecules, similar to process in volume D^- sources, but much more effective because of halogens' high electron affinities.

- Chose RF driven ion sources because arcs might be difficult to strike in strongly electronegative gases.

- H- sources use tandem discharge, with driver plasma with high energy electrons separated by magnetic filter from cooler extractor plasma; chose same configuration for halogens.

- Hydrogen negative ion sources require cesium for high current density, but not needed with halogens.

Current Densities Achieved in Initial Experiment

- RF source produced 45 mA/cm^2 of Cl^- or 53 mA/cm^2 of total positive ions with 2.2 kW of RF power (-/+ ratio of 0.79).

- At optimized conditions, co-extracted e^- current was only 7 times greater than Cl^- current, much less than to be expected from the difference in mobilities (240). Ratio was a factor of 30 more favorable with chlorine than with less-electronegative oxygen.

- Negative atomic chlorine current density not very sensitive to pressure; scaled linearly with RF power; should scale to around 100 mA/cm^2 at 5 kW in this small source (power supply limit was 2.2 kW)

•Second Experiment to Directly Compare Cl and Ar

- **Used one source, extraction optics, and set of diagnostics (Faraday cup and dual slit emittance scanner) so systematic errors are similar.**

- **Compare beams extracted from ion-ion electron-poor plasmas to beam from electron-ion plasmas.**

- **Chlorine and argon are similar in mass, but Cl has large electron affinity (3.61 eV) and argon has essentially none, so Cl plasma can approach ion-ion (Cl^{+}+ Cl^{-}) conditions, while Ar plasma will be (Ar^{+}+ e^{-}).**

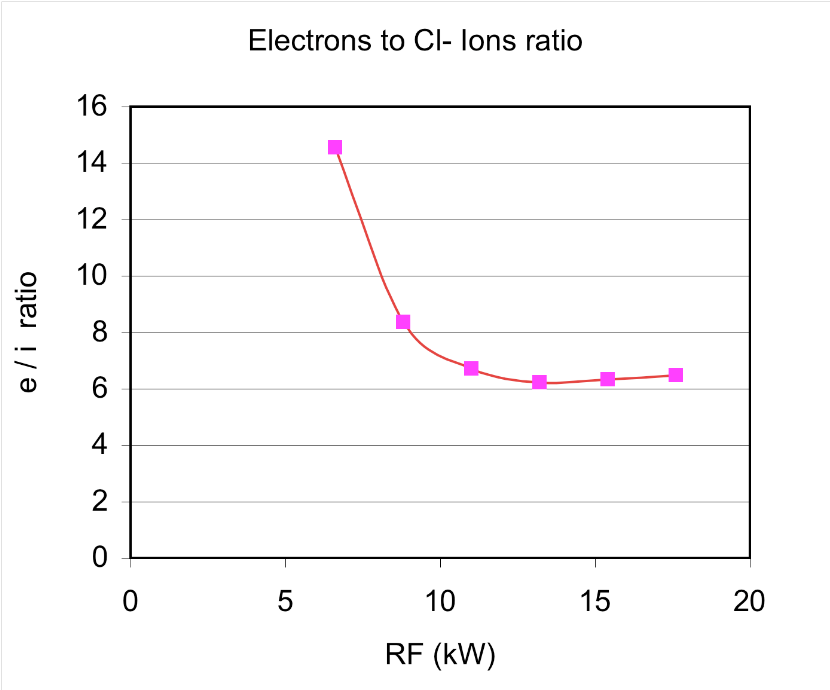
- **Measure Cl^{+}, Cl^{-}, e^{-}, and Ar^{+} relative current density and emittance at similar discharge parameters.**

Current Densities of Cl^-, $Cl^+ + Cl_2^+$, Ar^+ Are Quite Similar

- Because the cusp confinement field is about half the strength in this source of the one used earlier, and the RF power density is lower, the absolute current densities are lower than in the first experiment; but goal is to compare relative Cl^-,Cl^+,Ar^+.

- At 30 kV extraction, 7 kV RF drive, and 1.5 - 2 mtorr:
  - 15.5 mA of Ar^+
  - 13.9 mA of $Cl^+ + Cl_2^+$
  - 11.8 mA of Cl^-
  - Current ratios of: 1 : 0.89 : 0.76

Best e^-/Cl^- Ratio is about the Same as in the First Set of Cl^- Experiments Using a Different Source and Test Stand



At their minimum the electrons contribute only about 3% to extraction perveance, because they move much faster than Cl^-.

Electrons are measured with the Faraday Cup moved to intercept the deflected beam; this Data at 3.4 mtorr.

Mass mobility ratio would be 240.

Emittance Levels of Cl^-, $Cl^+ + Cl_2^+$, Ar^+ Are Very Similar

- Because ion optics contributes to emittance, can only set approximate upper limits on effective beam ion temperatures. In general, the emittance of all three beams is similar at any given perveance.

- The lowest normalized emittance at a given perveance is about the same for the three beams; for instance, at .09 nanopervs, it is
  - 0.0055 pi-mm-mrad for Ar^+
  - 0.0049 pi-mm-mrad for $Cl^+ + Cl_2^+$
  - 0.0049 pi-mm-mrad for Cl^-

  - Extending the emittance diagram to nearly 100% of the beam (and including extractor diameter of 0.25 cm) would give an effective beam ion temperature of about:

    T_{ibeam} = 0.34 eV for all three beams,
    if there were no optics contribution at the minimum emittance.

Similarity of Negative and Positive Chlorine Currents Demonstrates that Attenuation Is Tolerable

- The loss cross sections for heavy singly charged positive and negative ions of similar mass differ most at the low energies found in the initial extraction from an ion source. At higher energies, multielectron loss events are similar for both species.

- In the second experiment, the positive and negative ion currents had passed at low energy (12 - 30 keV) through a line density equivalent to passage through about 1.2 km of 1 x 10^{-8} residual N_2 in an accelerator.

- Equivalent to passage through many km at the much higher average energies in a heavy ion fusion accelerator.

- Despite this, the Cl^- current reaching the Faraday cup was 85 - 90% of the positive chlorine current, showing that the attenuation was very similar, since the negative ion density could never equal the positive ion density in the source, due to the need for some electrons to sustain dissociative attachment.

- Demonstrates that the halogen negative ions, with electron affinities of 3.02 -3.62 eV, are much more robust than H^- with an electron affinity of 0.75 eV.

Negative Halogen Driver Beams Appear Practical

- At similar discharge parameters, Cl^-, Cl^+, Ar^+ have similar:
  - –Emittance
  - –Effective beam ion temperature

- At similar discharge conditions, Cl^- and positive chlorine currents are similar ($Cl^-/Cl^+ + Cl_2^+$ was 85 -- 90%), and Cl^- is only modestly less than A r$^+$current (Cl^-/Ar^+ = 76%).

- Cl^- survives extraction with acceptable attenuation, rest of trip through an accelerator should be even easier

- In both experiments, best e^-/Cl^- ratio is low (about 7) with no electron suppression in extractor, probably partly because of internal magnetic filter, but also probably because of ion-ion electron-deficient extractor plasma.

- Other halogens (fluorine, iodine, bromine) should behave in similar fashion.

•Both Sets of Chlorine Experiments with Different Sources Exhibit Strong Evidence of Ion-Ion Plasmas in Extractor Region

- Near equality of Cl^- and Cl^++Cl_2^+ currents (79% -/+ in first source, 85-90% -/+ in second source) implies near equality in plasma, with little room for e^-.

- Low ratio of coextracted electrons: best e/Cl^- in first experiment is 7, at same condition where Cl^-/Cl^++Cl_2^+ maximum; e/Cl^- is 6 - 7 in second source, much less than mobility ratio.

- Extracting from single aperture, would expect (excluding magnetic effects) that for T_e= T_i e/Cl^- ratio should be square root of mass ratio: 240 if they were equally abundant in plasma, so measured e/Cl^- 35 times lower suggests relatively few electrons in the ion-ion plasma.

•Comparison with Oxygen Plasma Strengthens Evidence for $Cl^- + Cl^+ + Cl_2^+$ Plasma with few electrons

- Comparison of chlorine (3.61 eV electron affinity) to oxygen (electron affinity 1.46 eV) show strong scaling of ion-ion plasma formation with electron affinity:
  - Best $O^-/O^+ + O_2^+$ ratio is 25%.
  - e/O^- ratio was 300; larger than $T_e = T_i$ mobility of 160; shows electrons hotter than ions.

- Same magnetic filter and source produce:
  - e/Cl^- ratio of 6 - 7, which is 1/35th of $T_e = T_i$ mobility.
  - e/O^- ratio of 300, which is 2.25 of $T_e = T_i$ mobility.

- Demonstrates that low e/Cl^- ratio primarily reflects ion-ion extractor plasma with few electrons; not an artifact of fringing magnetic field of filter magnets.

•Weak Responses to Filter Position, Bias, and Cesium Are Supportive of Ion-Ion Plasma in Extractor Region

- When magnetic filter distance from extractor grid is varied from 1.1 cm to 2.1 cm, lowest e/Cl^- ratio occurs at 1.6 cm:
  - Confirms that low e/Cl^- ratio is not artifact of fringe filter field at extractor, which is a maximum with the 1.1 cm position.

- Unlike case with H, adding cesium to Cl has negligible effect, suggesting Cl^- already occupies most of negative charge phase space in plasma.

- Response to biasing plasma grid positive relative to plasma decreases strongly with electronegativity of discharge gas:
  - In H^- sources of this type, bias can double H^- while decreasing electrons.
  - Bias of up to 15 volts with oxygen produces 20% increase of O^- and 25% decrease of electrons.
  - Bias of up to 40 volts with chlorine produces negligible effect on Cl^- current, and reduces electrons by only 10%.
  - Consistent with reduced electron content and saturated Cl^- fraction in extractor plasma.

•Ion-Ion Plasmas Should Be Interesting and Useful State of Matter

- Producing ion-ion plasmas in beam source is convenient, because can extract the plasma components and measure their characteristics.

- In ion-ion plasmas most of the negative charge carriers are about the same mass as the positive charge carriers, and thus have the same mobility; very different from normal electron-ion plasma.

- Would expect from theory that ambipolar potential fluctuations should be lower due to much larger average mass of the charge carriers, leading to lower ion temperatures for both the positive and negative ions than for the ions in electron-ion plasmas.

- Experiments find low beam minimum beam temperature for beams from both ion-ion and ion-electron plasmas, but ion-ion not appreciably colder.

- This was probably because optics masked temperature, but could also be because ion-ion plasmas behave differently than expected.

What If Ion- Ion Plasmas Really Are Colder than Electron - Ion Plasmas?

- It would mean that, with appropriate extraction optics, the beams from such plasma could be focused to smaller spot sizes
- Thus, halogen ion-ion plasmas would be the best beam source choice for heavy ion fusion regardless of whether one wanted negative or positive ion beams
- Colder positive or negative ion beams, if used for ion lithography, would permit smaller feature sizes in producing masks for chip production in the semiconductor industry

Negative Ion Extraction from Plasmas

- It is difficult to extract negative ions from electron - ion plasmas because ambipolar diffusion produces a positive potential well to balance the diffusion of heavy positive ions and much lighter electrons

- It is easy to extract negative ions from ion - ion plasmas because the dominant negative charge carriers have about the same mass and mobility as the positive charge carriers, so ambipolar diffusion results in little, if any, opposing positive potential well

- Hydrogen is only weakly electronegative (0.75 eV, as compared to the halogens, which vary from 3.06 to 3.61 eV), so the negative ion sources used for H^- and D^- have electron - ion plasmas with a minority of negative ions

- The large negative hydrogen ion sources used for heating and current drive in magnetic fusion energy applications use magnetic fields to restrict electron diffusion to the extraction plane (effectively add mass to the electrons)

Halogen-Assisted Extraction of H^- and D^-

- Our halogen ion - ion plasma work suggests an alternative approach:
- Try adding a halogen to hydrogen plasma to see if this increases the amount of H^- which can be extracted, while decreasing the electrons, by producing ion - ion plasma characteristics
- Try chlorine first, since can simply be added to hydrogen plasma
- If this works, try iodine, since heavier halogen would result in fewer halogen negative ions being extracted with H^- or D^-

Caveats:

(1) Requires tilting accelerator so co-extracted halogens stopped at extractor

(2) Only works if are not already extracting most H^-

(3) Halogens and cesium form a salt, so best without Cs

•Extend Ion-Ion Plasmas to Warm Dense Matter Regime

- Heat micron thick foil of bromine or iodine with brief intense ion beam.
- Start with a salt (potassium chloride) on a gold or carbon substrate
- For moderate cost beam facility best approach is to pick beam and foil thickness such that beam enters at energy just above top of dE/dX peak and exits at low energy edge of peak; using only the top of the peak assures both maximum energy density deposition and best uniformity.
- Example: 1 MeV He^+ beam extracted from 5 cm radius multiaperture source could deposit 1.5 x 10^{11} J/m^3 in a 1 mm radius spot through a 1 micron foil with longitudinal uniformity of 4%, heating target to 0.3 eV
  - would require drift compression of 200 nanosecond beam to 1 nanosecond and very strong focusing element, not yet demonstrated.
- If can heat to a few tenths of an eV, form weakly ionized plasma; halogens can form negative ions by dissociative attachment of low energy electrons to ground state molecules as well as excited, so ion-plasma may form through pathways analogous to Cl ion-ion source plasmas.

•Ion-Ion Plasmas Produced from a Foil Might Exhibit an Additional Characteristic Not Observable in Sources, But Making Measurements Will be Challenging

- Ion-ion plasmas in our source experiments must have a small component of electrons to maintain dissociative attachment process; pulses are very long compared to molecular time scales.

- Foil experiment could produce ion-ion plasma in tiny area in short time, then expand, so remaining electrons, which would be much higher velocity than ions, might have chance to briefly expand away from ions, leaving a nearly pure ion-ion plasma in the center for a very brief period (limited by space charge attraction).

- Such a pure ion-ion plasma should exhibit ion conductivity similar to an electrolyte, in which the current is carried by the ions rather than electrons.

- Challenges: hard to measure conductivity on nanosecond time scale, and any electrons near the pure ion-ion plasma region will strongly interfere with measurement.